FRIB

# ECR ion sources for the Facility for Rare Isotope Beams (FRIB) project at Michigan State University

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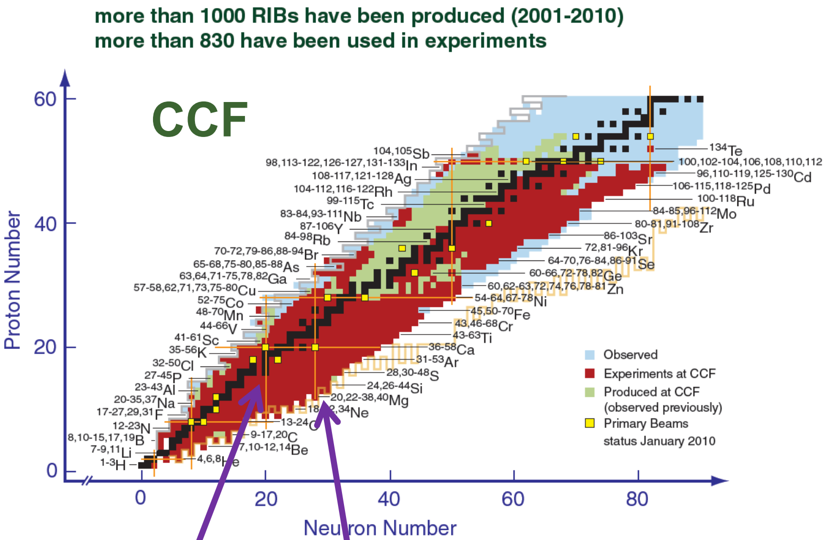
U.S. DEPARTMENT OF ENERGY | Office of Science

# Outline

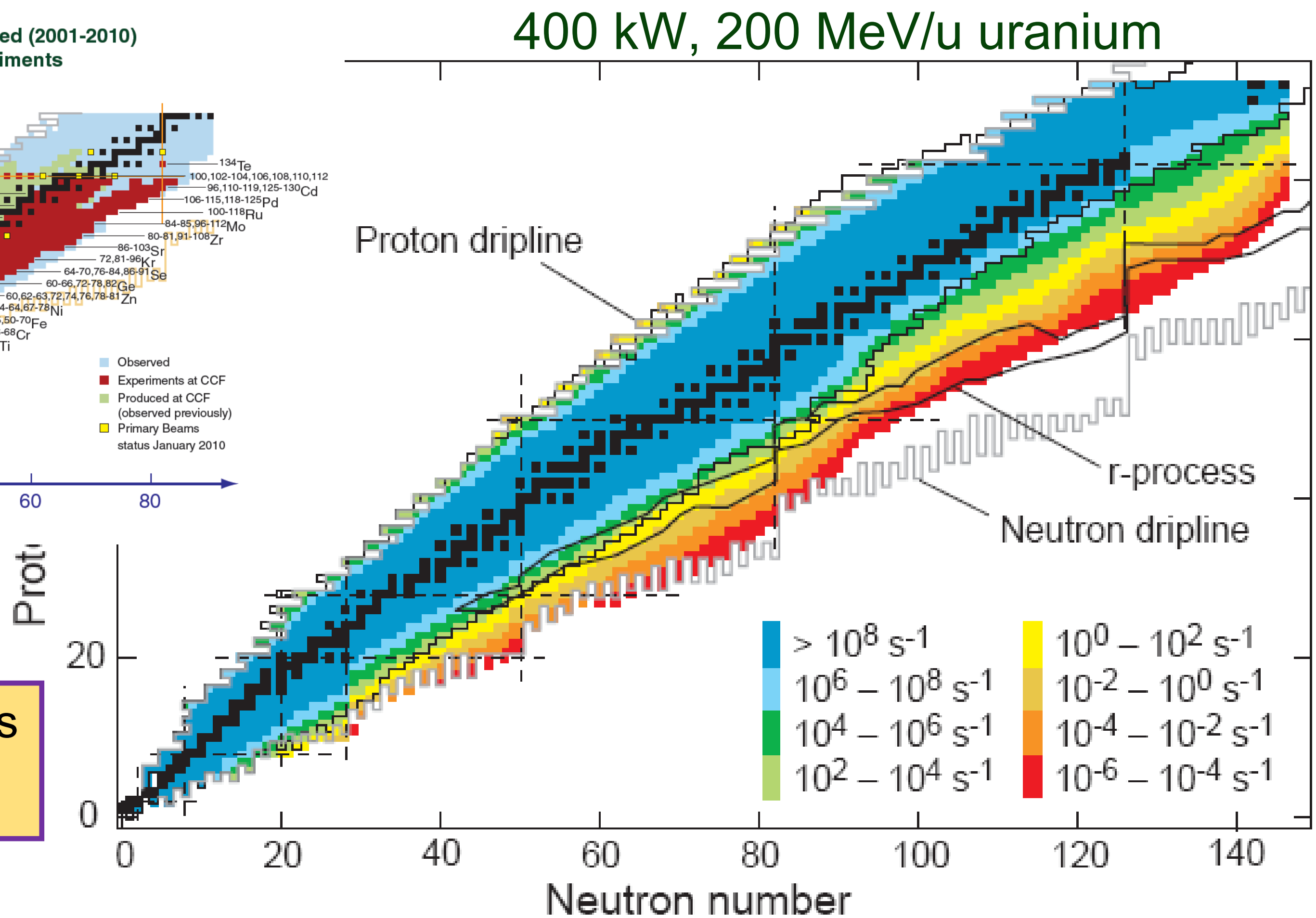
- Overview of FRIB Facility
- FRIB Linac Front End
- Ion sources for FRIB
  - Requirements
  - Conceptual Design
  - Challenges and development
- Summary and status

# FRIB Rare Isotope Beams



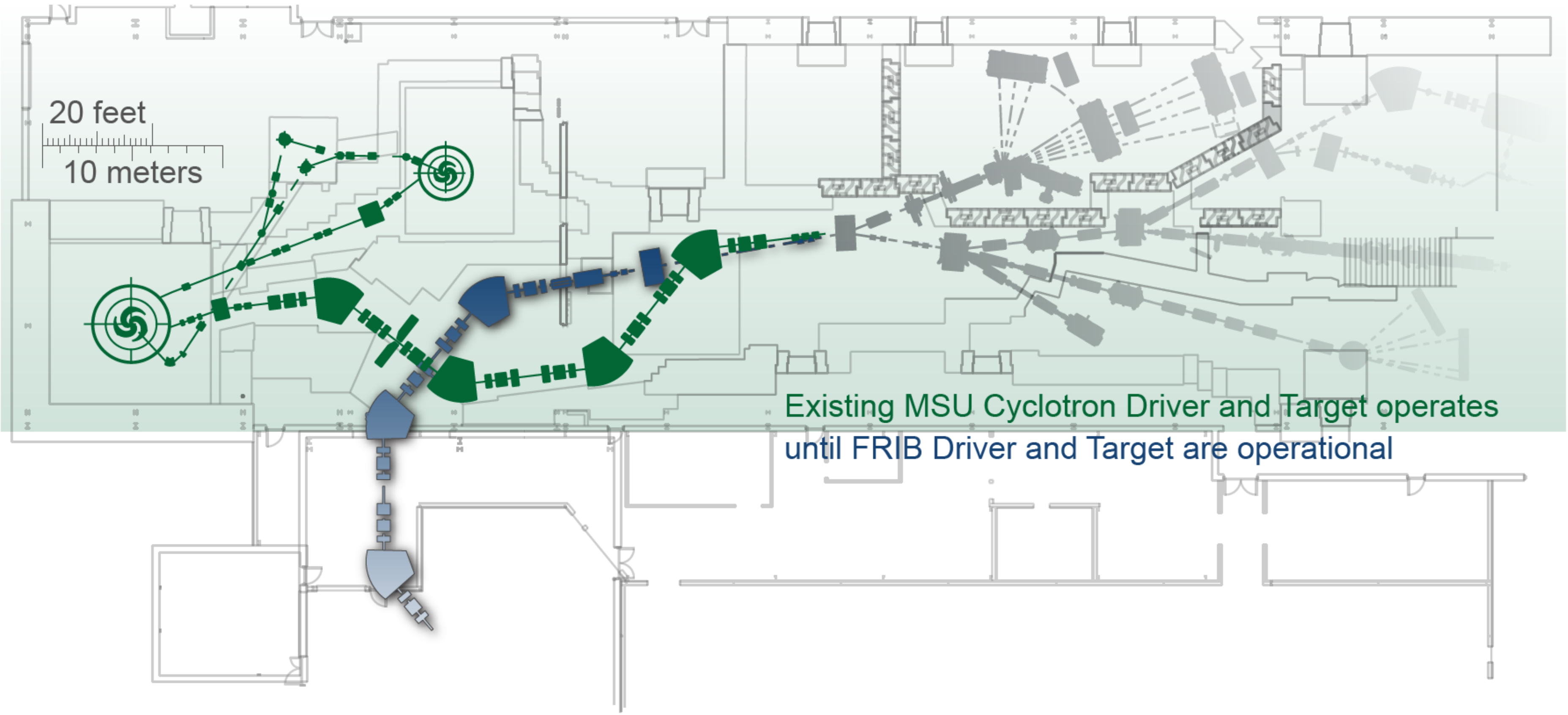

$^{46}$Ar ~10$^{7}$pps

$^{40}$Mg ~ 10$^{-6}$ pps
(2 / week)



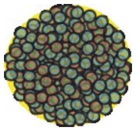

**Gain factors of 10-10000 over operational and planned facilities**

# Transition from NSCL to FRIB Operations



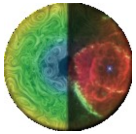

FRIB DRIVER

# Science with FRIB



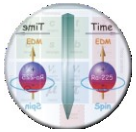
## Properties of nucleonic matter

- Classical domain of nuclear science
- Many-body quantum problem: intellectual overlap to mesoscopic science – how to understand the world from simple building blocks



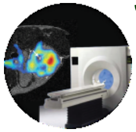
## Nuclear processes in the universe

- Energy generation in stars, (explosive) nucleo-synthesis
- Properties of neutron stars, EOS of asymmetric nuclear matter



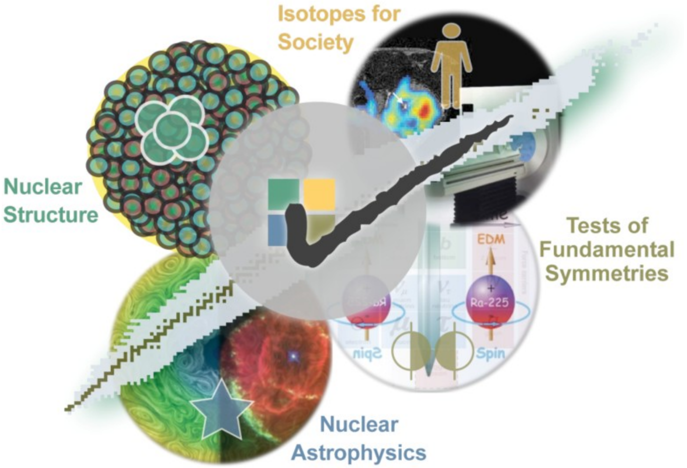
## Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

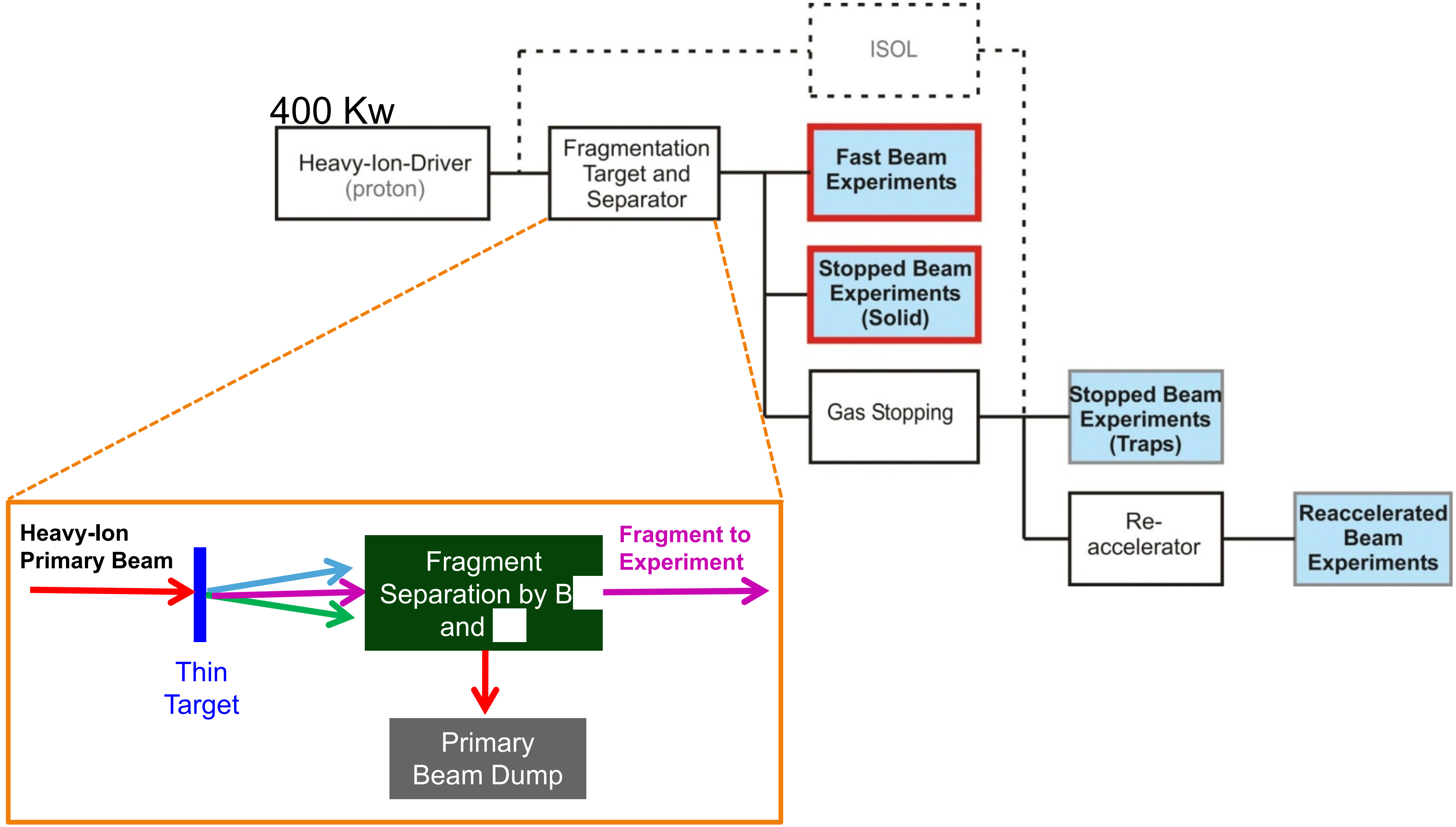


## Societal applications and benefits

- Bio-medicine, energy, material sciences, national security



# FRIB Rare Isotope Beams

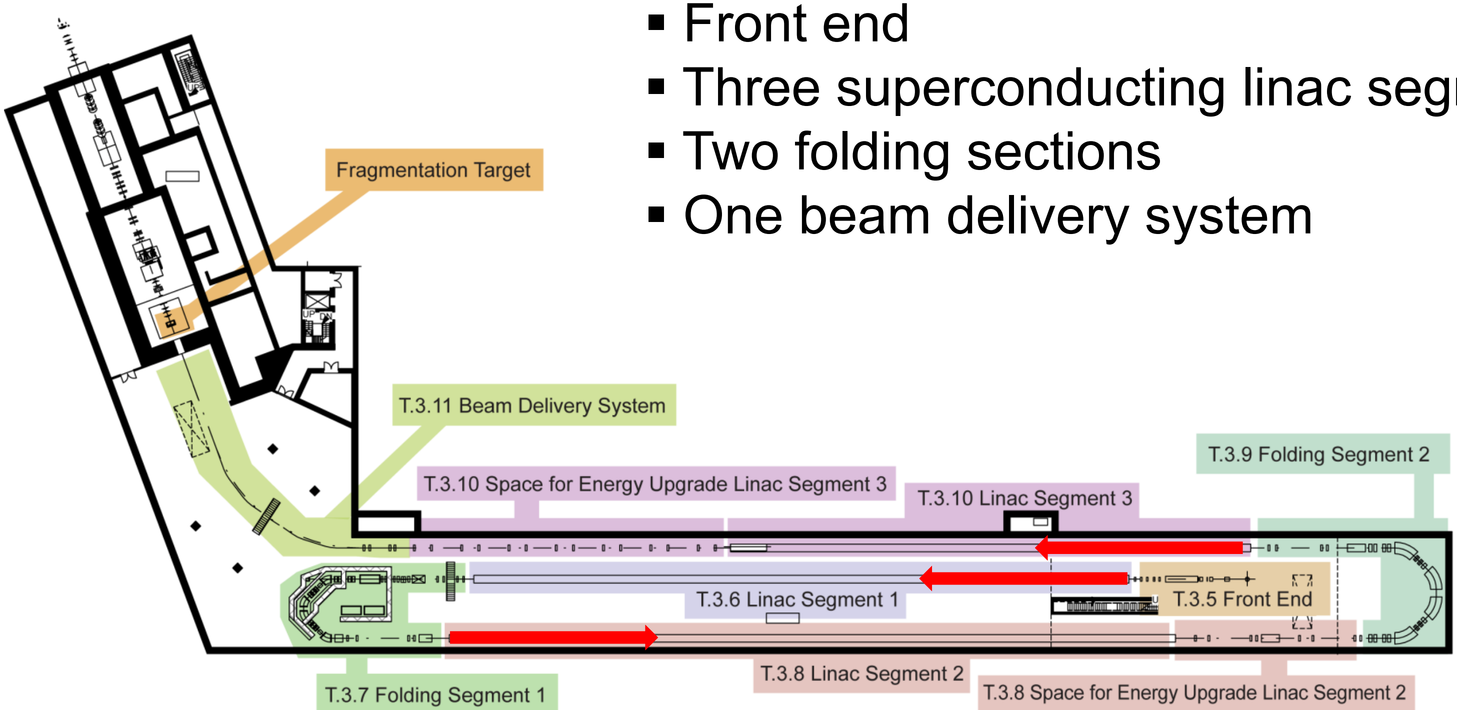


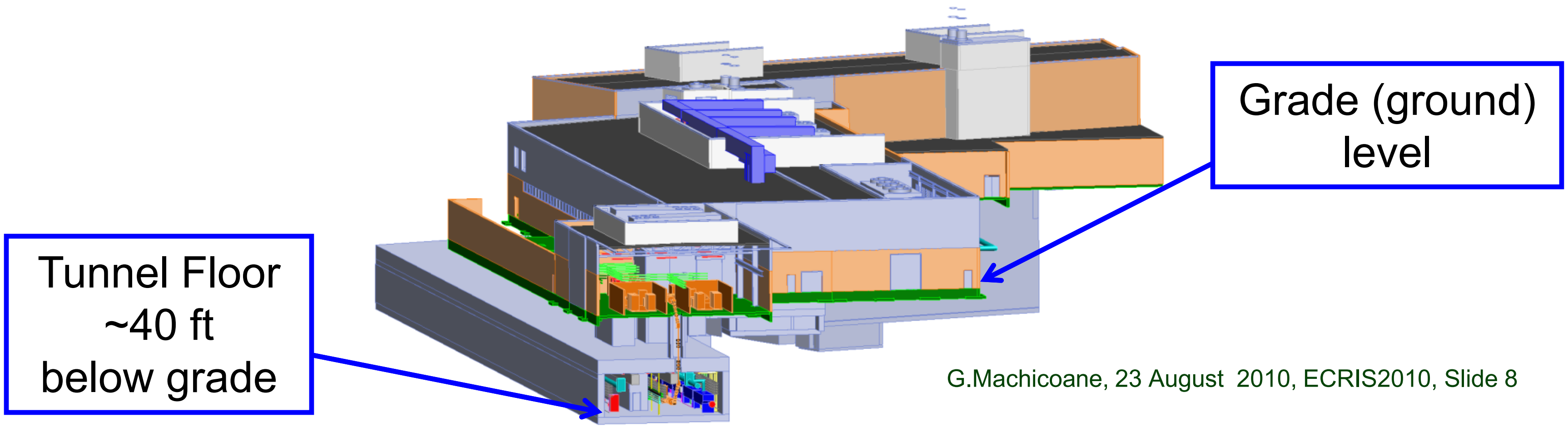
# FRIB Layout


SOUTH SHAW LANE
EXISTING NSCL
BOGUE STREET
TARGET HIGHBAY
EXISTING SOUTH HIGHBAY
CRYOPLANT BUILDING
LINAC SUPPORT BUILDING
ECR AREA
LINE OF TUNNEL BELOW
WILSON ROAD

# Double-folded Linac

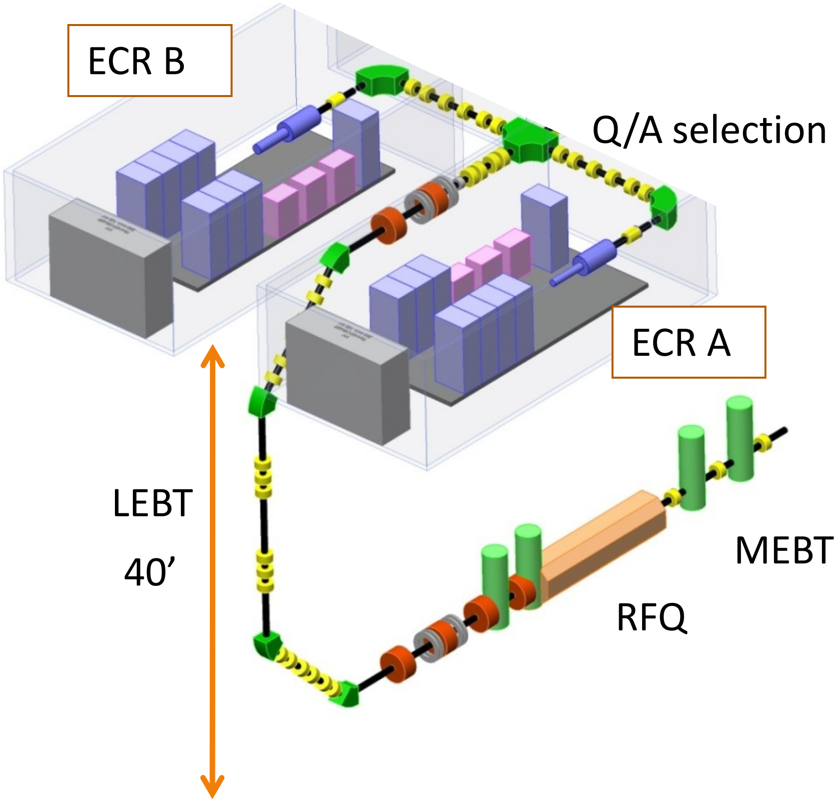
- Front end
- Three superconducting linac segments
- Two folding sections
- One beam delivery system



# Front End Components and their Functions

- **ECRIS on HV platform** (2) - generate ~400 eμA 12 keV/u ion beams (oxygen to uranium)
- **Achromatic charge selection system** (2) – select charge state(s)
- **LEBT** – transport beam, form beam emittance and time structure
- **RFQ** – accelerate beam to 300 keV/u
- **MEBT** – match beam to SRF driver linac



# FRIB Beam Intensity Requirement to Reach 400 kW on Target

| | A | Z | Q-ECR | Transmission(%) from ECR to Target | I-ECR (eμA) | I-ECR (pμA) |
|---|---|---|---|---|---|---|
| Argon | 40 | 18 | 8 | 80% | 378 | 47.3 |
| Calcium | 48 | 20 | 11 | 80% | 468 | 42.5 |
| Nickel | 58 | 28 | 12 | 80% | 365 | 30.4 |
| Krypton | 78 | 36 | 14 | 80% | 331 | 23.6 |
| Tin | 112 | 50 | 18 | 72% | 354 | 19.7 |
| Xenon | 124 | 54 | 18 | 72% | 334 | 18.5 |
| Lead | 208 | 82 | 27,28 | 64% | 392 | 14.3 |
| Bismuth | 209 | 83 | 28,29 | 64% | 404 | 14.2 |
| Uranium | 238 | 92 | 33, 34 | 64% | 424 | 12.7 |

# Other Requirements

- Beam energy extracted from ECR 12 keV/u [ECR + HV platform]
- Normalized full Beam emittance within 0.9 pi.mm.mrad for single charge state or 0.6 pi.mm.mrad for each charge state for 2 charge state transport
- Beam stability (TBD)
    - ECR typical stability for gas is approximately a few percent
- Maximize beam availability
    - Redundancy through 2 ion sources
- Beam extracted from ECR should have as little contaminant as possible
    - Flexibility on the selected charge state
    - Losses will be mostly in the bending section after the stripper

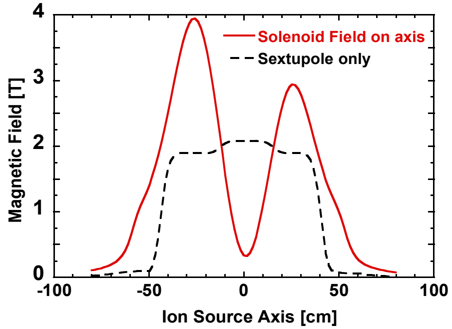
# ECR Conceptual Design for FRIB

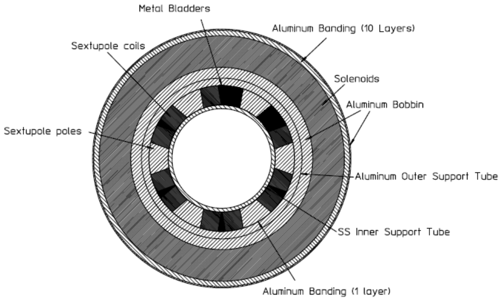
- FRIB ECR ion source based on VENUS ECR ion sources developed by LBNL with lessons-learned

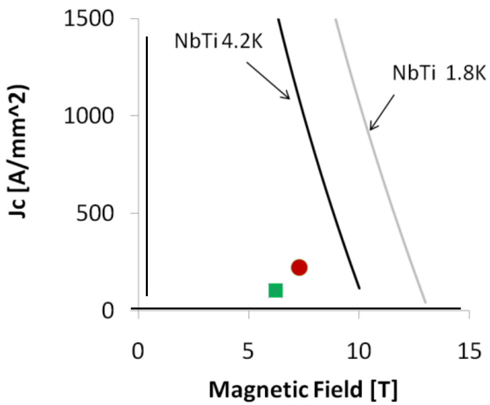
| | Charge State | Maximum Intensity Extracted [puA] | FRIB Intensity [puA] |
|---|---|---|---|
| **Uranium** | 33 or 34 | 6.21 | 12.7 |
| **Bismuth** | 28 or 29 | 8.45 | 14.2 |
| **Xenon** | 20 | 16 | 18.5 |
| **Argon** | 11 | 90.91 | 47.3 (8+) |
| **Oxygen** | 6 | 475 | 103 |

# Coil Package based on VENUS magnet

- Only coil that has demonstrated required magnetic field to operate at 28 GHz and can energize solenoids independently from sextupole coil
- No retraining needed after warm-up
- Innovative clamping techniques (Bladders)
- 3:1 Copper content in the sextupole wire,
- Shell construction to apply enough pre-stress
- Conservative approach for maximum field values and current densities to keep enough safety margin
- The coil package will be unchanged for FRIB
- Engineering during FY11

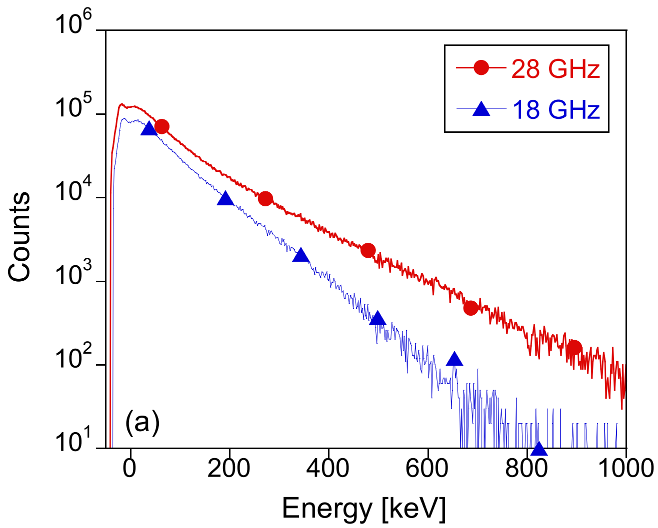


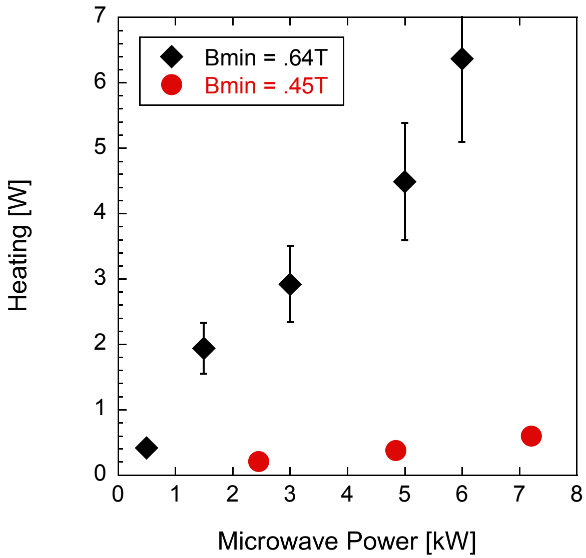



# Requirements for ECR Ion Source Cryostat for FRIB

- 28 GHz heating results in higher x-ray flux and higher x-ray energies
  - The cryostat for the ECR ion source needs to have a cooling capacity above 13W-15W at 4.2K

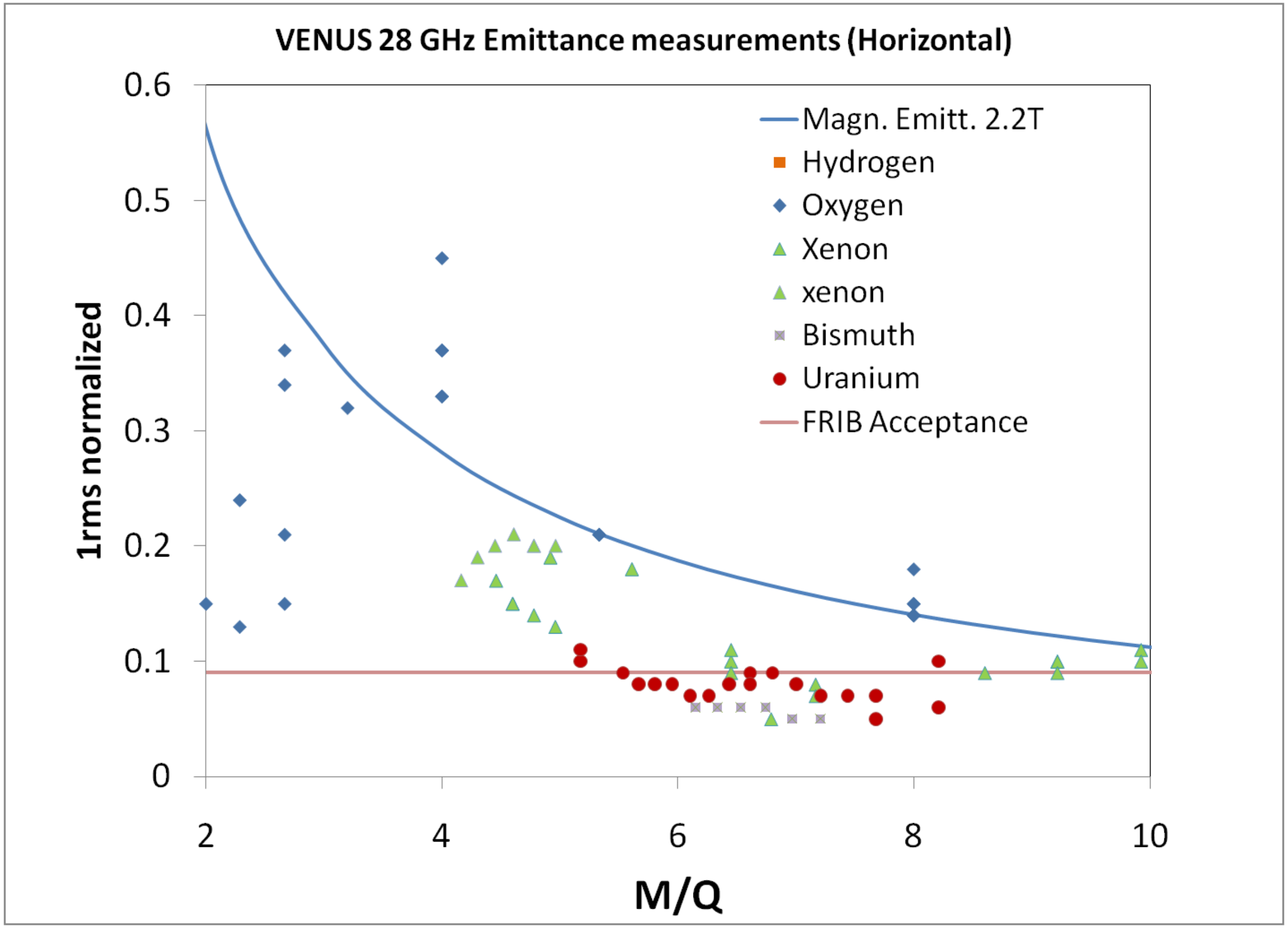



- HV platform operation require a closed loop refrigeration system
  - Cryocoolers (Gifford-McMahon (1.5W), Gifford-McMahon/Joule-Thomson (4-5 W)
  - Refrigerator (Liquefier with compressor on HV platform)

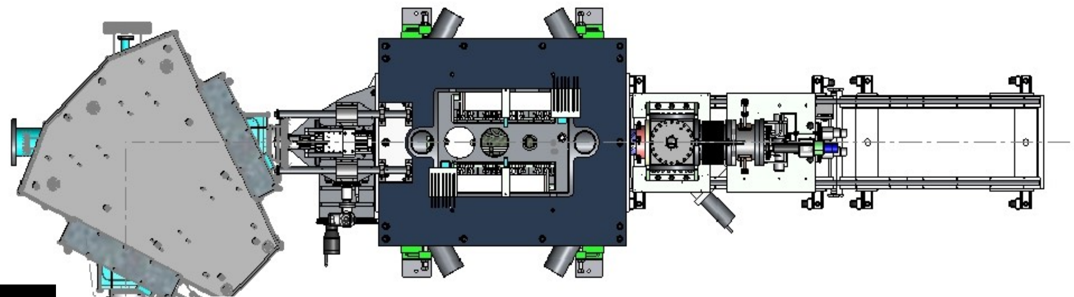
- Challenges for FRIB ECR ion sources

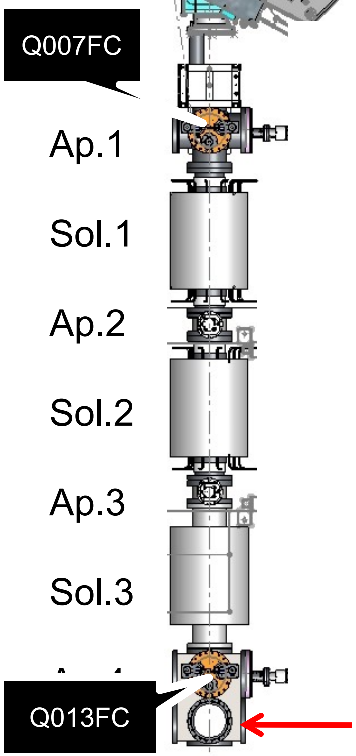
# Emittances from ECR Ion Sources: VENUS




- For the same M/Q the emittance values are lower for heavier masses
- Emittance decline for higher charge states (in many cases)

# SuSI set for FRIB measurements



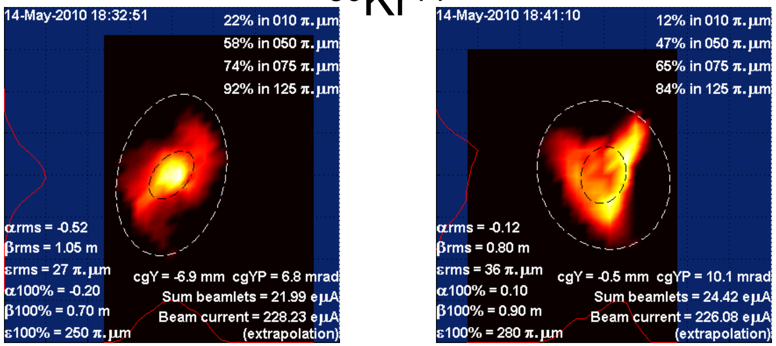



- D/2 = $\sqrt{\beta\varepsilon}$

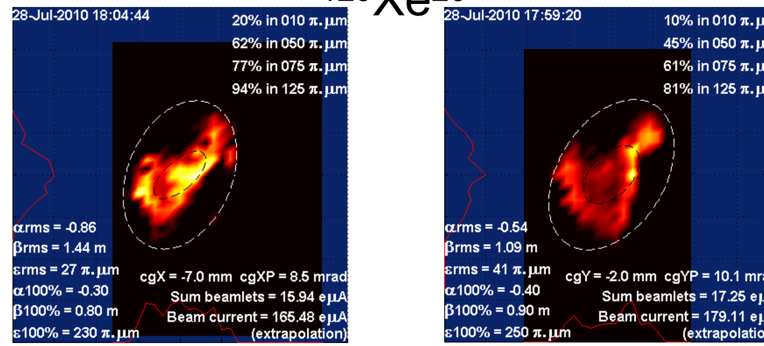
- 0.9 $\pi$.mm.mrad → 34mm
- 0.6 $\pi$.mm.mrad → 28mm

# Emittances from ECR Ion Sources: SuSI

$^{86}Kr^{14+}$



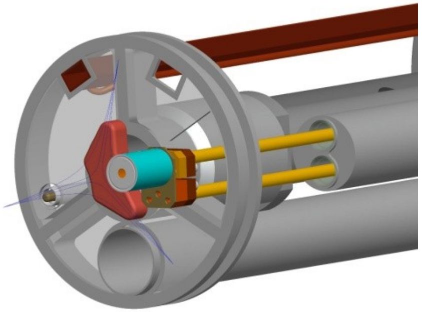

$^{129}Xe^{20+}$



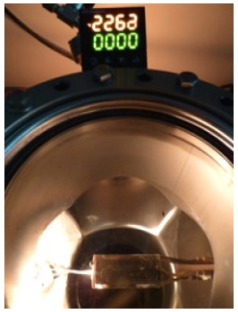

| | Charge State | Horizontal Emittance* | Vertical Emittance* | Beam Intensity Q013FC [euA] | Beam Intensity Q007FC [euA] | FRIB Intensity [eµA] |
|---|---|---|---|---|---|---|
| Xenon | 20 | 0.75 | 0.82 | **210** | **320** | **334** |
| Krypton | 14 | 0.82 | 0.92 | **250** | **380** | **331** |
| Argon | 8 | 0.88 | 0.82 | 400 | 600 | 378 |
| Oxygen | 6 | 0.56 | 0.52 | 600 | >1mA | 618 |

- **More measurements needed (drain current, charge…)**

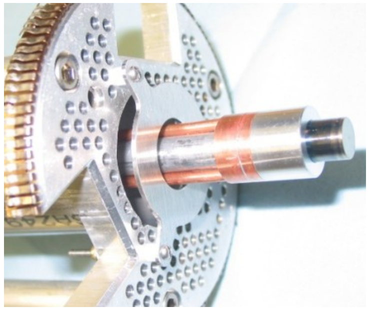
# Uranium Beam Development



- Resistive oven
  - $URe_2$ /UO2
  - Ta Oven temperature at 2000 C
  - More than 220 eμA for $U^{33+}$ and $U^{34+}$ (But limited by vapor available)
  - (Meet FRIB Requirement for Uranium production)
  - New axial oven (Ta /Re)

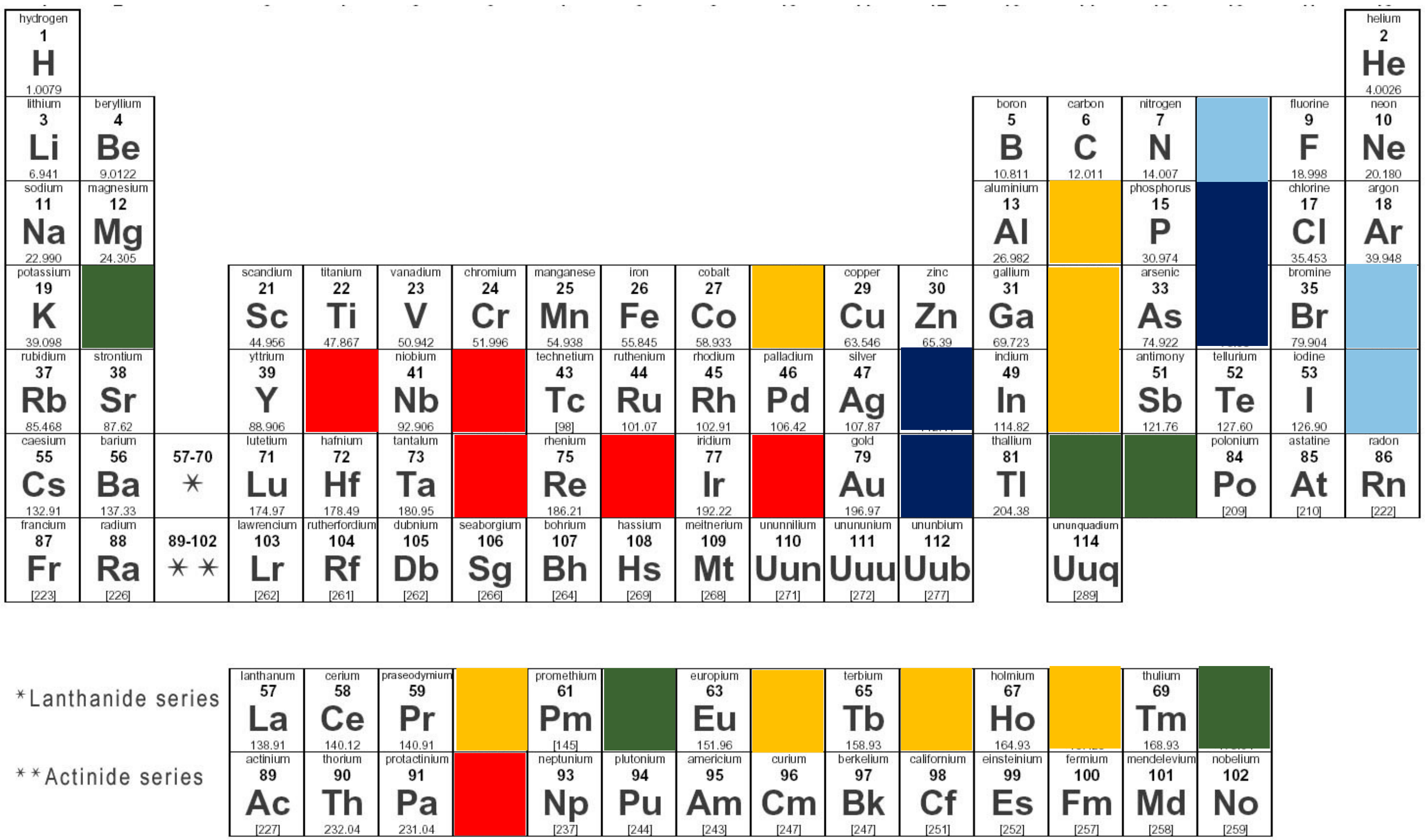


- Inductive oven
  - UO2
  - Rhenium susceptor with Hf02 thermal insulator
  - temperature to limit of thermocouple (2300 C)
  - 50 eμA of $U^{33+}$ (limited by vapor available)



- Sputtering
  - depleted U target
  - Axial positioning
  - 1 cm diameter sample/ water-cooled holder
  - >80 eμA of $U^{33+}$

# Metallic Beam development for FRIB

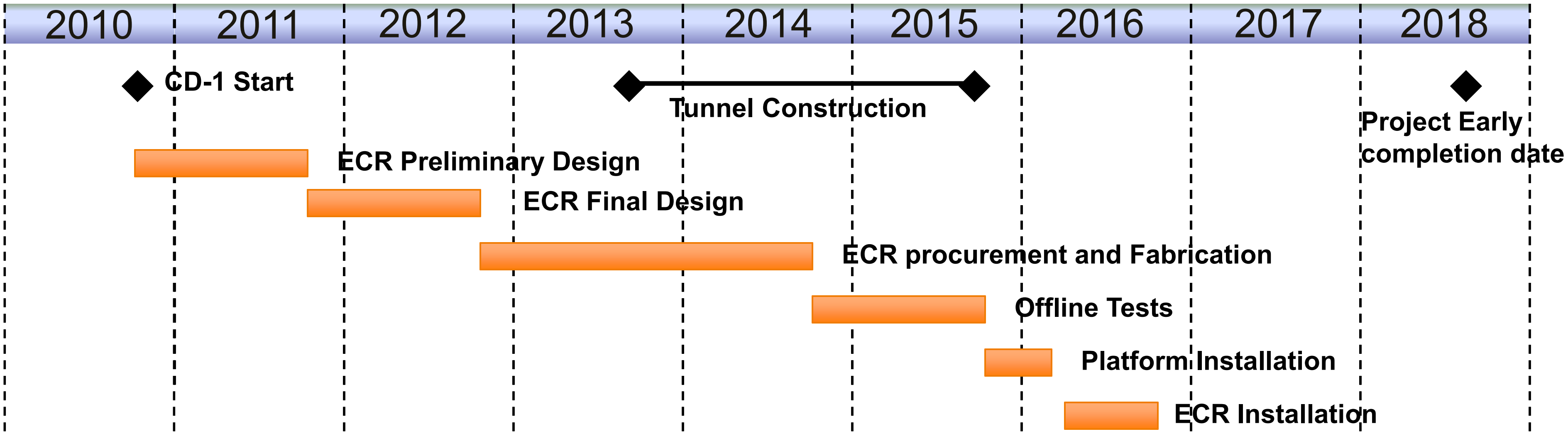



T>2000 °C | 2000 °C>T>1000 °C | 1000 °C>T>500 °C | T<500 °C

| Ranking | Beam | abund. |
|---|---|---|
| 1 | 238U | 99.30% |
| 2 | 204Hg | 6.90% |
| 3 | 82Se | 8.70% |
| 4 | 144Sm | 3.10% |
| 5 | 58Ni | 68.10% |
| 6 | 176Yb | 12.80% |
| 7 | 198Pt | 7.20% |
| 8 | 48Ca | 0.19% |
| 9 | 106Cd | 1.25% |
| 10 | 92Mo | 14.80% |
| 11 | 78Kr | 0.35% |
| 12 | 124Sn | 5.80% |
| 13 | 184Os | 0.02% |
| 14 | 196Hg | 0.15% |
| 15 | 160Gd | 21.90% |
| 16 | 76Ge | 7.60% |
| 17 | 150Nd | 5.60% |
| 18 | 124Xe | 0.09% |
| 19 | 204Pb | 1.40% |
| 20 | 156Dy | 0.06% |
| 21 | 186W | 28.40% |
| 22 | 136Xe | 8.90% |
| 23 | 170Er | 14.90% |
| 24 | 28Si | 92.20% |
| 25 | 64Ni | 0.93% |
| 26 | 190Pt | 0.01% |
| 27 | 112Sn | 0.97% |
| 28 | 96Zr | 2.80% |
| 29 | 209Bi | 100.00% |
| 30 | 16O | 99.80% |
| 31 | 168Yb | 0.13% |
| 32 | 174Hf | 0.16% |
| 33 | 64Zn | 48.60% |
| 34 | 36S | 0.02% |

# Project Status

- CDR (Conceptual Design Report) completed and reviewed by DOE-July 2010
- Project ready for CD-1 (Preliminary design) for FY2011

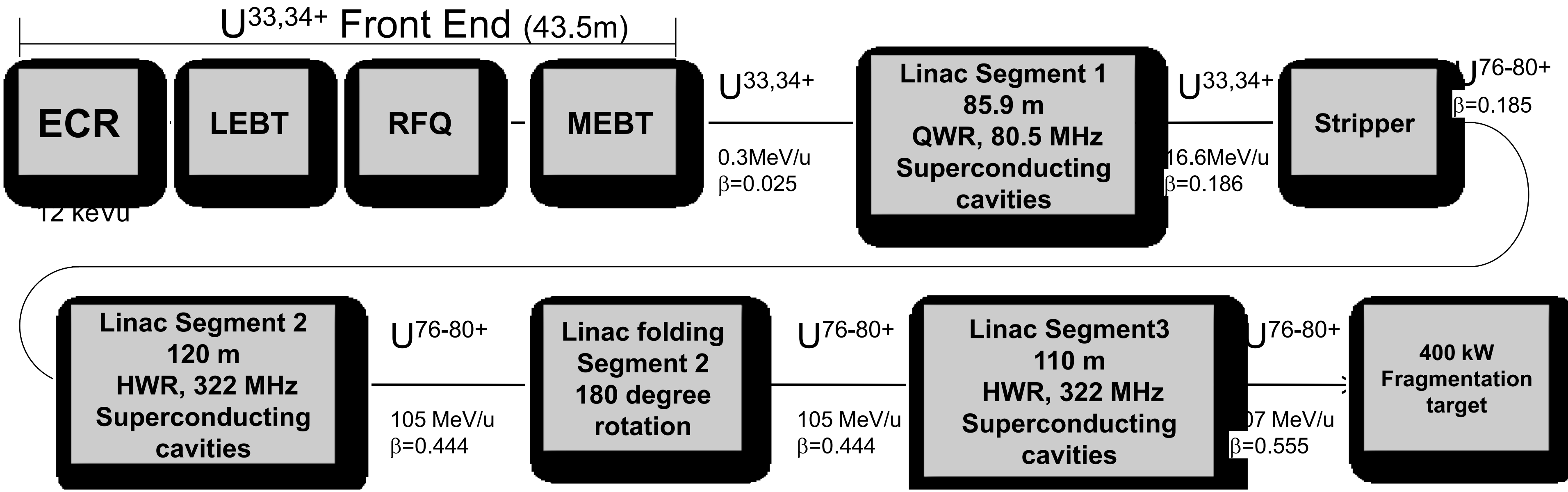


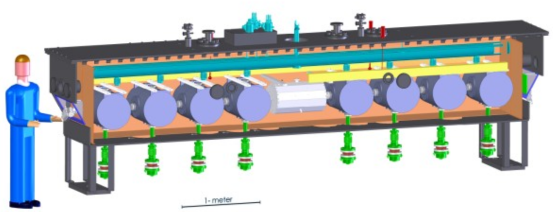
# FY2011

- Emittances measurements with high intensity beams
  - SuSI
  - VENUS
  - SECRAL

- Engineering of coil package and cryostat of FRIB ECR based on venus
- Evaluation of cold Box option

# FRIB Driver Linac Schematic

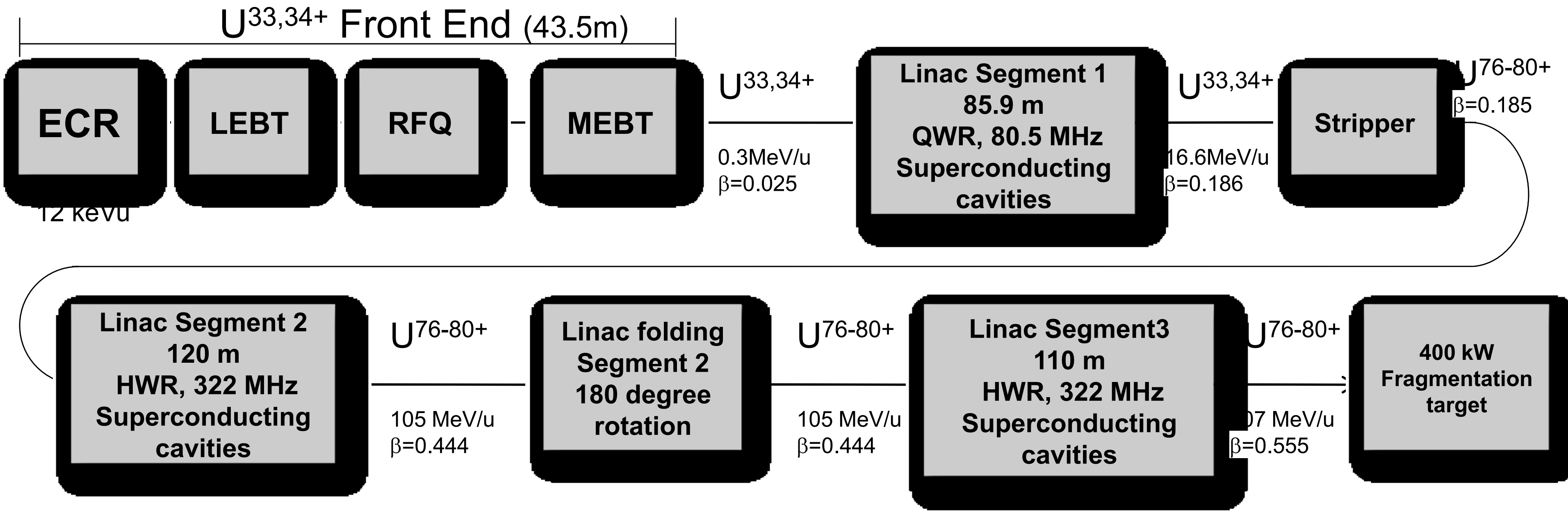


β=0.530 Cryomodule

- Baseline: 11 λ/2 cryomodules
- Space for 7 additional cryomodules
- Uranium beam acceleration:
  - Solid stripping ~ 200 MeV/u
    - » 11 cryomodules (78+)
  - Gas stripping
    - » +2 cryomodules (74+)
    - » +7 cryomodules (63+)

# FRIB Driver Linac Schematic



# Required Modifications to VENUS Cryostat

- Modifications are needed to the VENUS cryostat to ensure a cooling capacity exceeding 10W at 4.2K
  - Combination of 2 single (5W) and 2 double stage (1.5W) cryocoolers
  - Single stage cryocooler at 50K for precooling the normal conducting leads
  - Optimize coupling of the cryocoolers and serviceability of the cryocoolers heads
  - Optimize cryostat design to minimize static heat load (1W)
  - Add access ports to the cryostat to ease serviceability and maintenance
  - Add redundant instrumentation for Helium level and Helium pressure

# Challenges for FRIB ECR Ion Sources(II)

- Beam stability at a high current needs to be further characterized
- High power operation might represent a risk
  - » Plasma instabilities can damage the plasma chamber(VENUS)
  - » High level of X-rays generate high heat load in cryostat, can cause quenches
  - » Substantial X-ray shielding will be required for personnel safety
- Optimize Solid Material consumption
  - » Material consumption is estimated to be about 5 to 10 mg/hr
- Contamination by analog beam (i.e. M/Q) will represent a source of losses in the LINAC

# Challenges for FRIB ECR Ion Sources

- Intensity requirement:
  - State of the art ion sources do not meet FRIB requirements for heavy elements in a single charge state. To meet FRIB requirement, 2 charge states will be accelerated simultaneously.
  - High intensity of medium masses ($^{48}Ca$, $^{58}Ni$, $^{76}Ge$) metallic beam have seldom been reported

- Emittance of beam extracted from ECR ion source
  - Emittance growth due to magnetic field (angular momentum)

$$\varepsilon_{MAG}^{xx'-rms-norm} = 0.032 \cdot r^2 \cdot B_0 \cdot \frac{1}{M/Q}$$

  - Case of large extracted beam currents
    - » Space charge forces